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GUIDELINE ON PROBABILISTIC FRACTURE MECHANICS ANALYSES FOR JAPANESE REACTOR PRESSURE VESSELS

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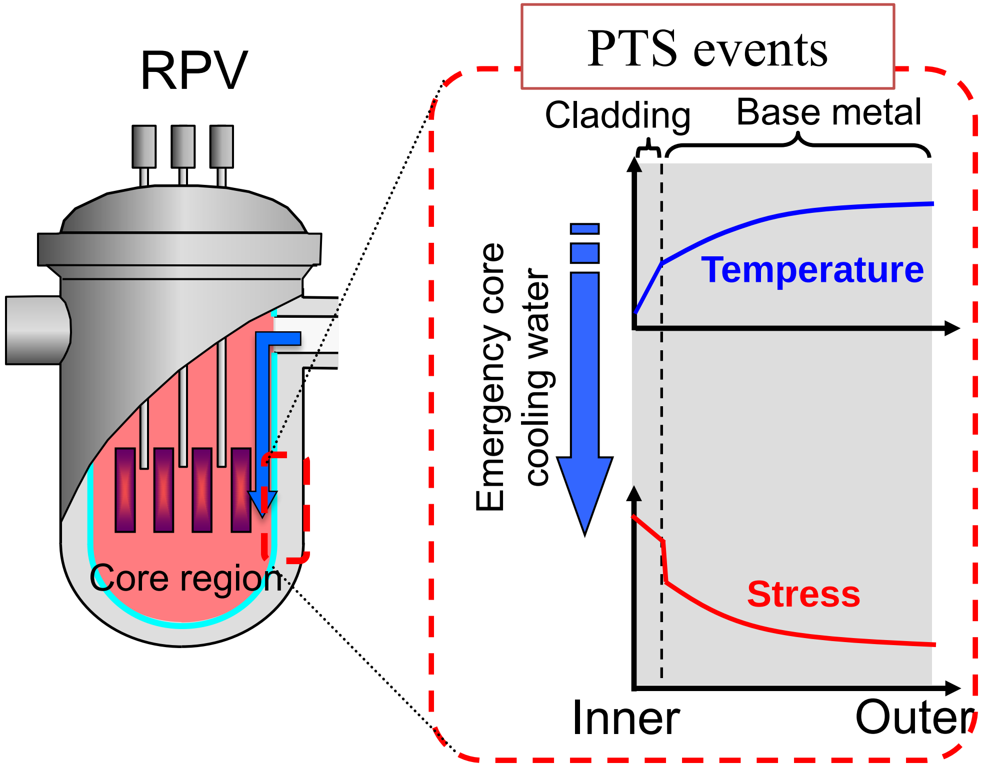
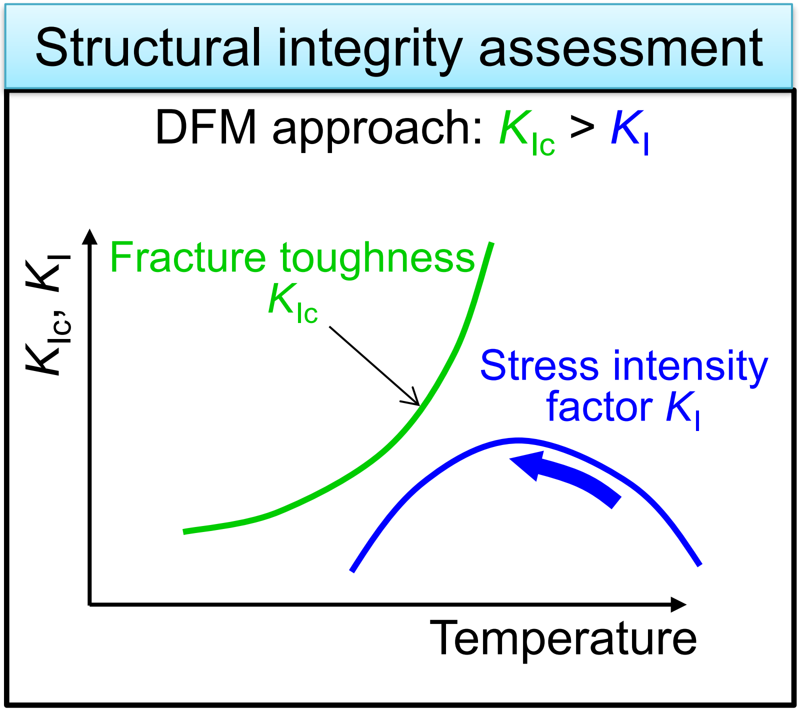
Background

- Reactor pressure vessel (RPV) is one of the most important components in nuclear power plants (NPPs).
- Pressurized thermal shock (PTS) events are the most severe conditions challenging the structural integrity of RPVs exposed to neutron irradiation.
- In Japan, deterministic fracture mechanics (DFM) is currently used in the structural integrity assessment of RPVs taking neutron irradiation embrittlement and PTS events into account.





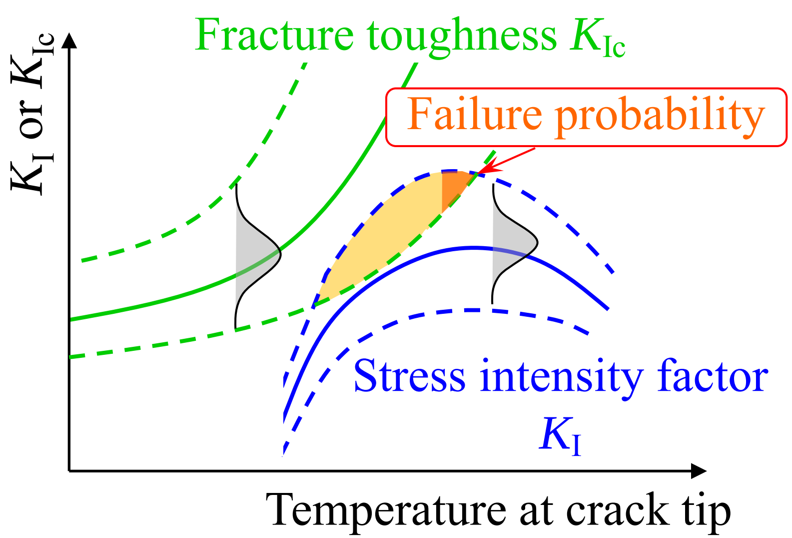
Background

- Probabilistic fracture mechanics (PFM) has been recognized as a promising methodology in structural integrity assessment of RPVs because it can rationally represent the influence parameters in their inherent probabilistic distributions without over conservativeness.
- In our JAEA, a PFM analysis code PASCAL* has been developed for Japanese RPVs.

***PASCAL** (PFM Analysis of Structural Components in Aging LWR)

Structural integrity assessment

PFM approach: Failure probability



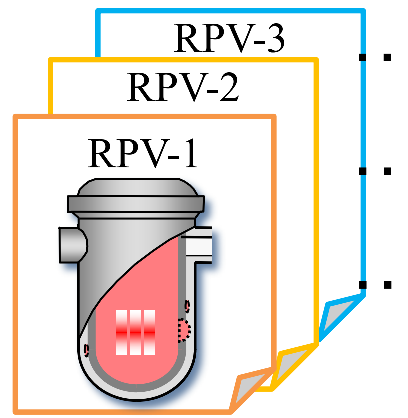
CPF and CPI

- Conditional probability of failure (CPF):

$$CPF = \frac{\text{Failed RPVs}}{\text{All sampled RPVs}}$$

- Conditional probability of crack initiation (CPI):

$$CPI = \frac{\text{Crack initiated RPVs}}{\text{All sampled RPVs}}$$



Overview of Our Project

The project to improve the applicability of PFM to Japanese RPVs

Development of Analysis Model, Methodology, and Code

- Fracture toughness and crack arrest toughness models
- Weld residual stress simulation
- Stress intensity factor evaluation methods, etc.

⇨ PASCAL

Development of PFM Guideline

- Description and explanation of the key points and technical basis of PFM analysis.
- Standard analysis method, typical analysis data, typical analysis results, etc.

Verification & Validation of PFM Analysis Code

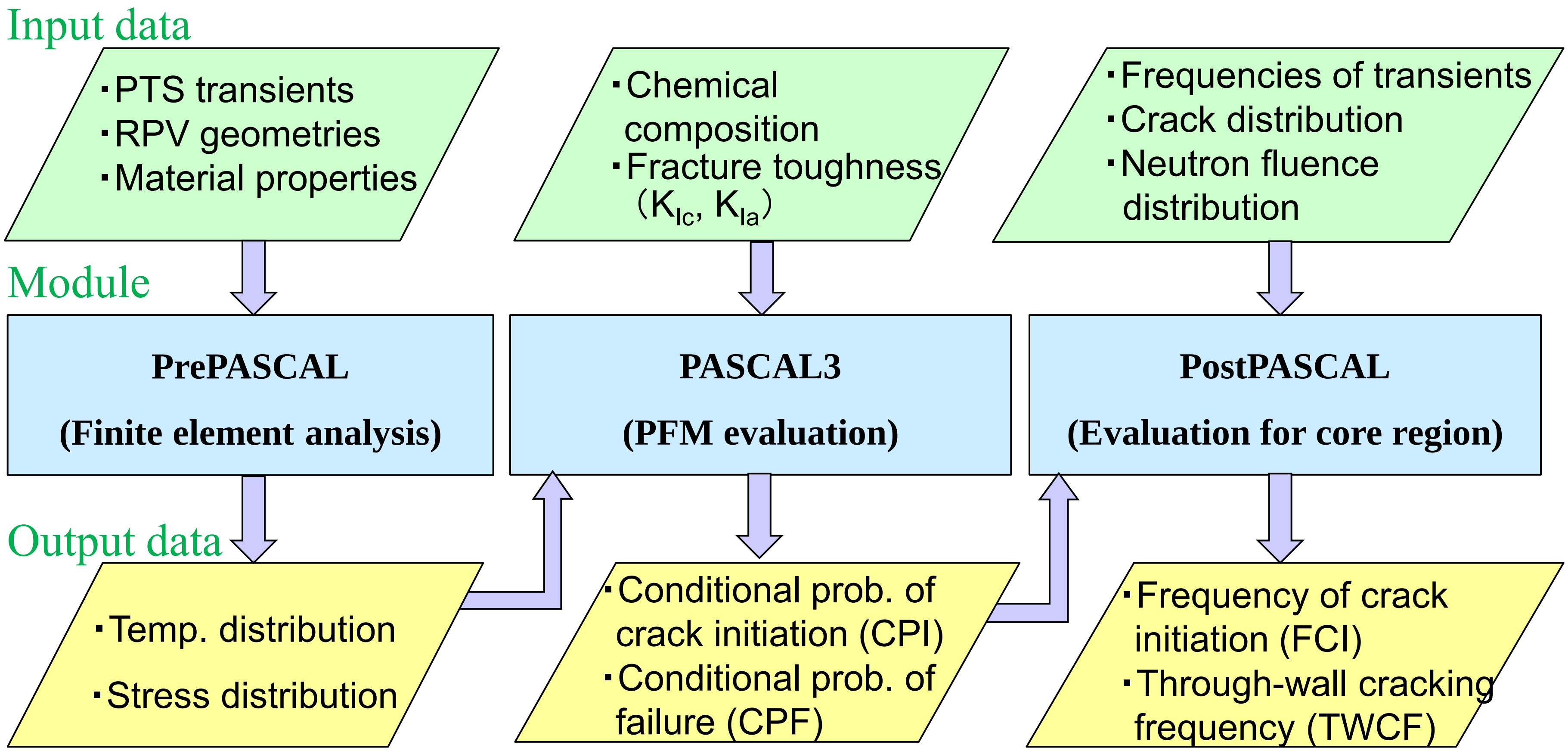
- V&V of PASCAL
- Domestic and international round-robin & benchmark analyses
- Release and check the source program in a Working Group established in Japan

Discussion on Application of PFM

- Application of TWCF, effect of Inspection, effect of countermeasures to improve safety margin, etc.

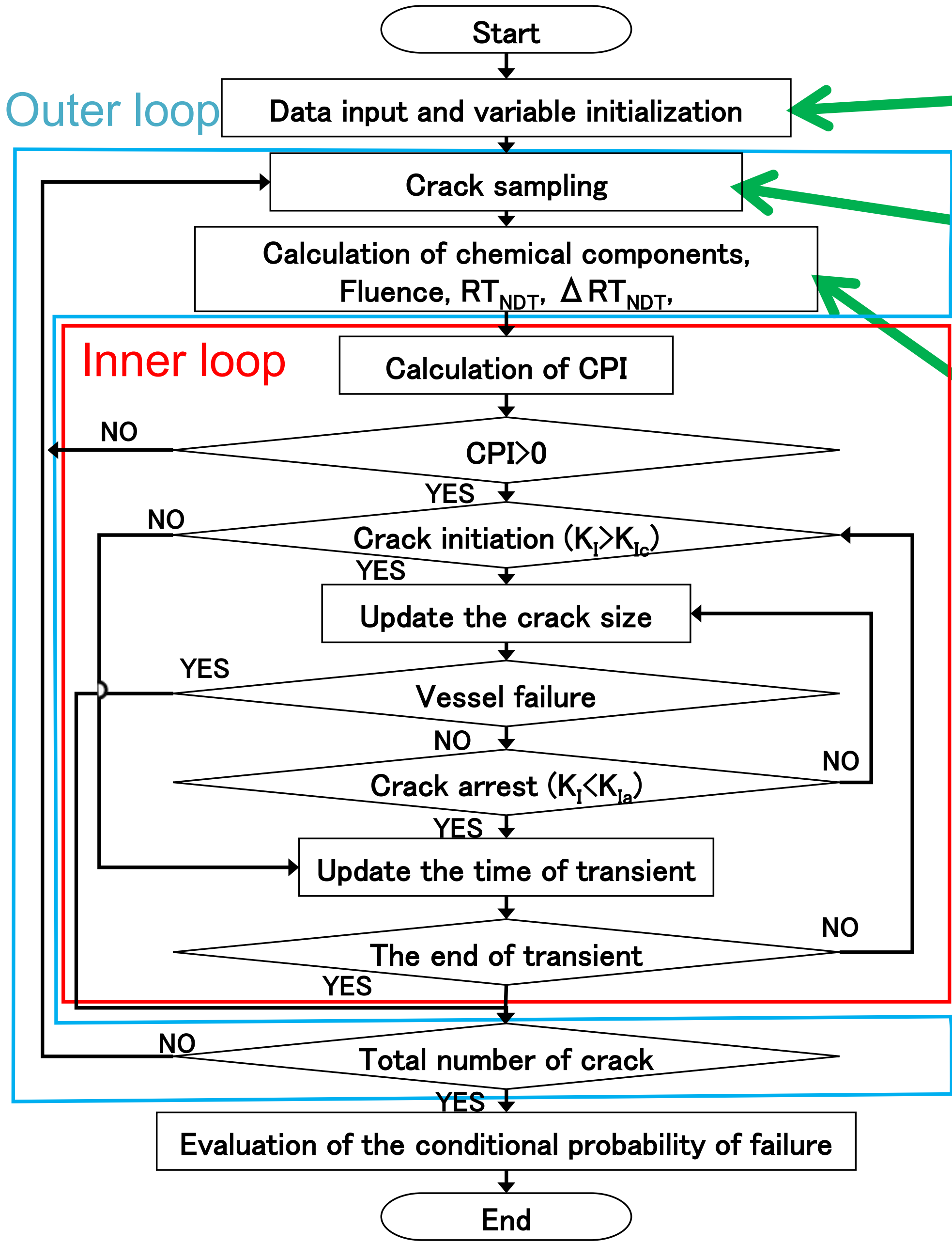
Outline of PASCAL

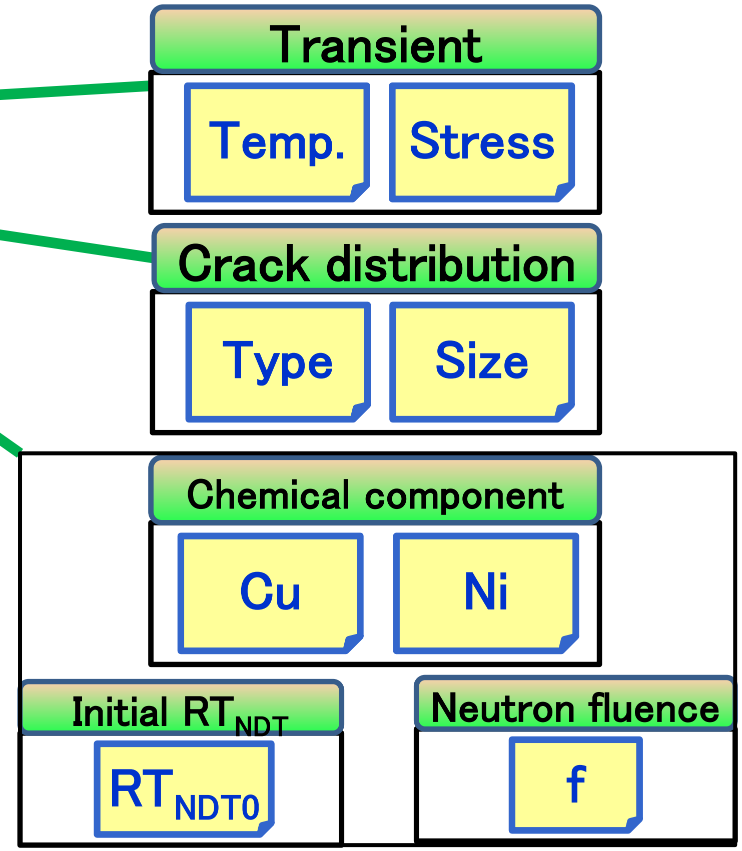
Target: Structural integrity assessment for Japanese RPVs



Structure and flow chart of PASCAL

Outline of PFM analysis module: PASCAL3





Aleatory uncertainty (e.g. K_{Ic}, K_{Ia})

Epistemic uncertainty (e.g. Cu, Ni, RT_{NDT}, f)

Verification of PASCAL

- Many activities have been conducted to verify PASCAL code.
  - ✓V&V activities for PASCAL code
  - ✓Domestic and international round-robin analyses
  - ✓Benchmark analyses of PASCAL with FAVOR*
  - ✓Release and check the source program in a Working Group established in Japan

Working Group on Verification of PASCAL

No.	Member	Abbreviation	Affiliation
1	Mitsubishi Heavy Industries, Ltd.	MHI	Industry
2	IHI Corporation	IHI	Industry
3	Central Research Institute of Electric Power Industry	CRIEPI	Institute
4	Nagaoka University of Technology	NUT	University
5	Ibaraki University	IU	University
6	Mizuho Information & Research Institute, Inc.	MHIR	Consulting
7	Japan Atomic Energy Agency	JAEA	Institute

*FAVOR is a PFM analysis code developed in the United States for RPVs and has been utilized in nuclear regulation.

Verification of PASCAL3

List of verification items in V&V activity

Category	Items
Probabilistic variables	Chemical composition
	Neutron fluence
	Reference temperature of nil-ductile transition (RT_{NDT})
	Fracture toughness (K_{Ic})
	Crack arrest toughness (K_{Ia})
	Crack size and distribution
	Frequency of transients
Analysis models	Stress intensity factor (K_I) solutions, Weight function method
	Irradiation prediction model
	Decay of neutron irradiation
	Fracture evaluation method
	Plasticity correction
Analysis algorithm or calculation flow	Conditional probability of crack initiation (CPI), Conditional probability of failure (CPF)
	Crack initiation and arrest
	Warm pre-stressing (WPS) effect
	Latin hypercube sampling (LHS)
	Frequency of crack initiation (FCI), Through-wall cracking frequency (TWCF)

- In order to achieve the objective that an engineer can perform the PFM analyses and evaluate TWCFs of RPVs without difficulty, we developed a PFM analysis guideline.
  - ✓ The guideline describes how to calculate failure frequency including TWCF of RPV and how to establish probabilistic evaluation models along with their technical basis.
  - ✓ To develop this guideline, an RPV structural integrity research committee was established. Several experts on structural integrity assessment of RPVs or PFM methodology are invited as members of the committee. A wide range of in-depth discussions on the application of PFM to Japanese RPVs were conducted.

- In the guideline, main body, and in the explanatio

Main bo

I. General items

II. PTS transients

✓ Cracks types and

III. Fracture toughness

✓ Reference tempe

IV. Failure frequency e

V. Analysis code

➢ References

➢ Appendix: Verification of PFM code

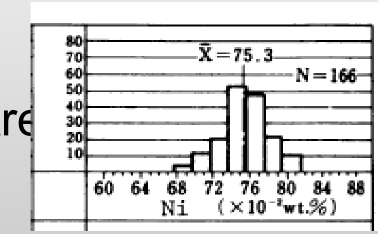
V. Analysis code

➢ Appendix: Examples for PASCAL

I. General items

II. PTS transients

- Selection of transients,
- Time histories of temperature and stre
- Weld residual stress distribution,
- Potential cracks,



III. Fracture toughness

- Neutron fluence

IV. Failure frequency evaluation

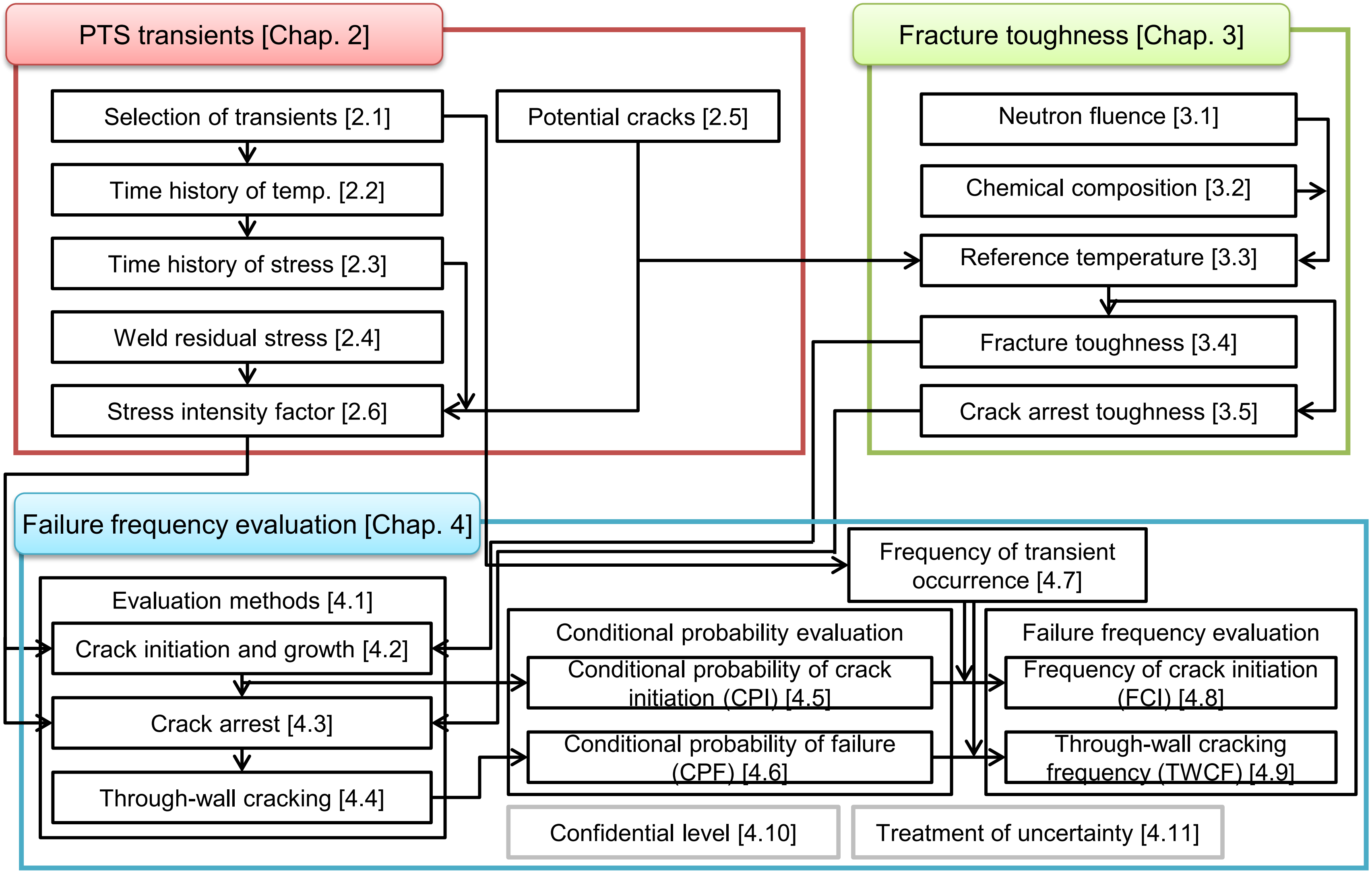
- Crack initiation and growth, crack arrest, through-wall cracking,
- Frequency of transient occurrence,
- Frequency of crack initiation, through-wall cracking frequency,
- Confidence level,
- Calculation accuracy

V. Analysis code

- Verification of PFM analysis code.

Guideline and Evaluation Flow

- The guideline prescribes the PFM analysis procedures covering all of the failure frequency evaluation flow.



PTS transients [...

Selection of tran...

Time history of

Time history of

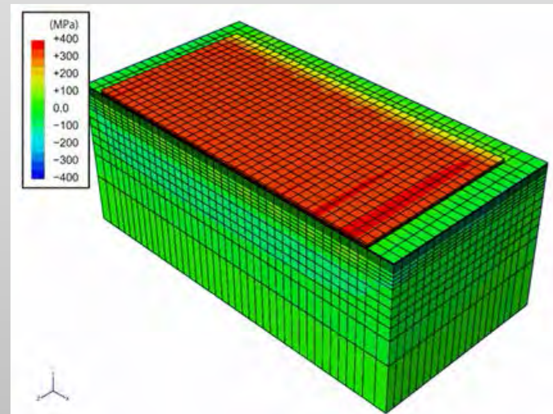
Weld residual s...

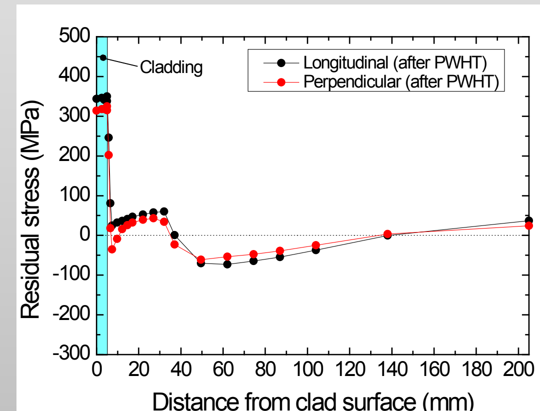
Stress intensity

K_I calculation method

We introduced high accurate K_I calculation methods such as weight function method to PASCAL3.

- Complicated distribution of weld residual stress considering phase transformation during welding.





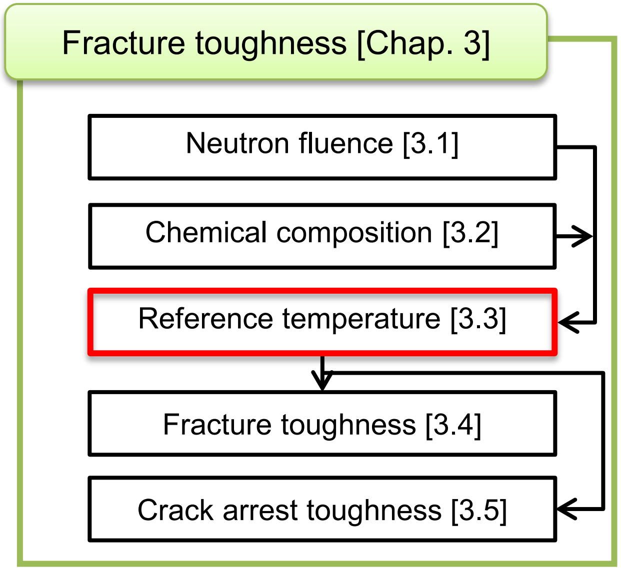
Bayesian ... method has been provided in NUREG-2163 for the case when there is indication detected by non-destructive examination.

➪ We proposed a Bayesian update method for the cases when there is indication and there is no indication detected during inspection, considering the Japanese situation.

- ... inspection results can also be incorporated in crack dimensions and crack density distributions.

➪ LBLOCA, SBLOCA, MSLB, SOV events*

* LBLOCA: Large break LOCA, SBLOCA: Small break LOCA, MSLB: Main stream line break, SOV: Stack open valve



3.3 Reference temperature (RT_{NDT})

- For calculating RT_{NDT} shift, the irradiation embrittleme 2007 (2013 for domestic
- Standard deviation 9.5°C and mean value of residual −1.1°C

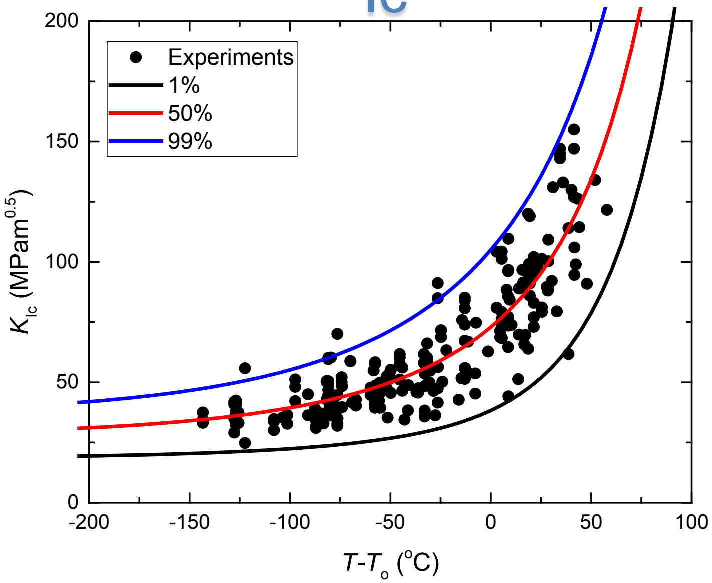
Standard deviation in irradiation prediction

Standard deviation and mean value of residual shall be taken into account based on the investigation on surveillance test data.

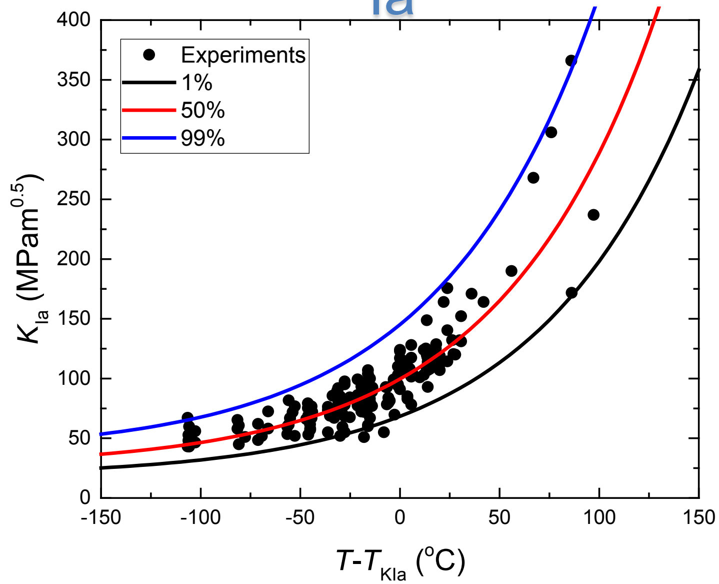
Chapter 3: Fracture toughness

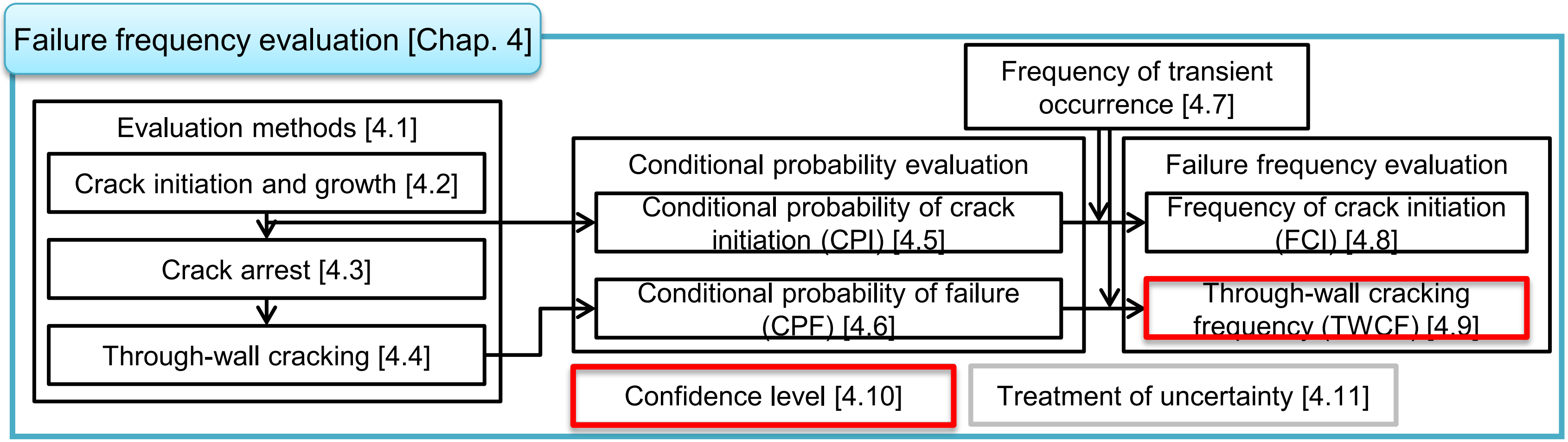
- To treat K_{Ic} and K_{Ia} as factors with aleatory uncertainties, the epistemic uncertainties included in RT_{NDT} should be modeled appropriately.
- To improve the applicability of PFM to Japanese RPVs, the evaluation models of K_{Ic} and K_{Ia} were established using a database of Japanese RPV steels.

K_{Ic}



K_{Ia}





4.9 Through-wall cracking frequency (TWCF)

- After multiplying CPF [4.4] by the occurrence frequency of each transient [4.7] and considering its distributions, a sum is taken over all selected transients.

4.10 Confidence level

- In the FCI and TWCF evaluations, it is recommended to perform PFM analyses by considering epistemic and aleatory uncertainties, to obtain the confidence values corresponding to percentiles.

Evaluation Functions and Input Data For Japanese Model RPV

- We selected evaluation functions and input data appropriate for evaluating a Japanese model RPV that satisfy the guideline.

Typical evaluation functions

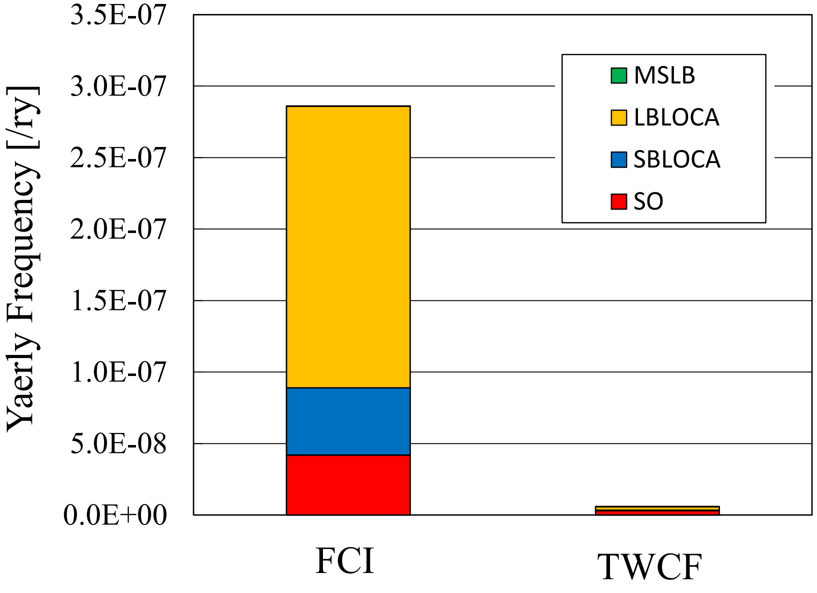
Irradiation embrittlement prediction		JEAC4201-2007 (sup. 2013)
Neutron attenuation		Exponential equation
Fracture toughness (K_{Ic})		Weibull type
Crack arrest toughness (K_{Ia})		Lognormal type
SIF calculation	K_I solutions	JSME code, RSE-M
	Weld residual stress	Weight function method, polynomial approximation from where a crack exists.
WPS effect		ACE model

Typical input data for Japanese model RPV

Item	Parameter	
PTS transients and their annual frequencies	LBLOCA: SBLOCA: MSLB:	6.7×10^{-5} 5.9×10^{-4} 2.2×10^{-3}
	SOV:	# 126: 1.87×10^{-4} # 60: 2.15×10^{-5} # 130: 3.09×10^{-5} # 97: 3.74×10^{-6} # 71: 3.74×10^{-6}
Potential Crack	Circumferential surface-breaking crack (base metal and weld regions), Axial and circumferential embedded crack (only in the base metal region)	
Mean value of maximum neutron fluence and SD	7×10^{19} n/cm^2 (E > 1 MeV; at 48EFPY) SD: 13.1% of mean value	
SD of initial RT_{NDT}	9.4° C	
SD of chemical composition	Cu: 0.01% Ni: 0.02%	

Analysis Results

- Typical analysis results
  - ✓Confidence levels of FCI and TWCF are obtained by PASCAL.
  - ✓Most cracks initiated near the inner surface during LBLOCA and SBLOCA might have been arrested.
  - ✓In SOV event, low temperature in the through-wall and higher inner pressure cause the highest contribution to TWCF.



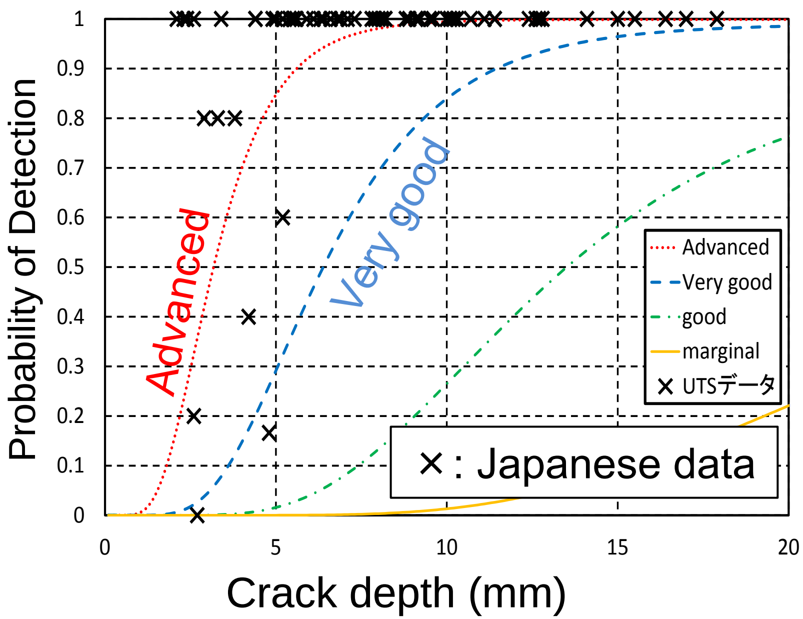
Confidence level

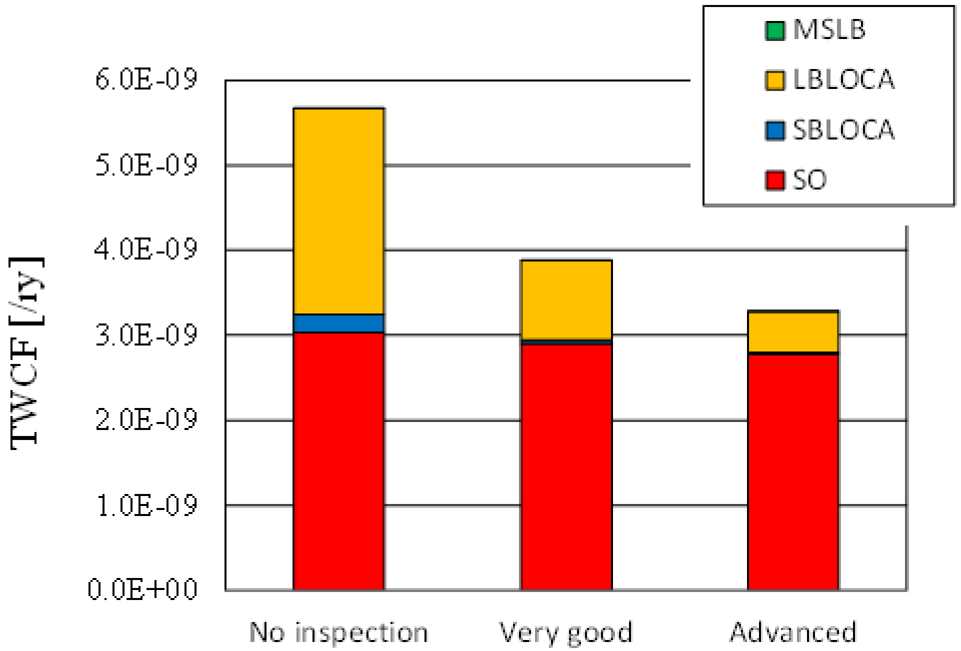
	Mean [/ry]	50 percentile [/ry]	95 percentile [/ry]	99 percentile [/ry]
FCI	2.9E-07	6.1E-14	7.9E-07	5.5E-06
TWCF	5.9E-09	5.9E-17	4.6E-10	1.7E-08

Contribution of transients on failure frequencies

	MSLB [/ry]	LBLOCA [/ry]	SBLOCA [/ry]	SOV [/ry]	Total [/ry]
FCI	4.7E-11	2.0E-07	4.7E-08	4.2E-08	2.9E-07
	0.0%	68.9%	16.4%	14.7%	-
TWCF	1.2E-12	2.5E-09	2.2E-10	3.1E-09	5.9E-09
	0.0%	42.7%	3.8%	53.5%	-

- Effect of Inspection on TWCF
  - ✓ The crack detection probability curves were set to "very good" and "advanced" in accordance with the Japanese inspection data.
  - ✓ It is assumed that there is no indication detected during inspection. Such results from the inspection were reflected in the crack density based on Bayesian update.





Summary

- As a part of our research on the application of PFM to the structural integrity assessment of Japanese RPVs, we have developed a guideline to provide the general procedures for using PFM to evaluate the structural integrity of RPVs.
- In addition, inputs, evaluation functions, and algorithms appropriate for failure frequency evaluations for a Japanese model RPV that satisfy the guideline were selected together with the technical basis.
- We confirmed that the guideline developed in this study is useful for failure frequency evaluations of Japanese RPVs.

ACKNOWLEDGEMENT :
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Thank you

for your attention!